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(54) IMPROVEMENTS IN OR RELATING TO HEAT EXCHANGERS

(71) We, KRAFTWERK UNION AKTIENGESELLSCHAFT, a German Company, of Mülheim (Ruhr), Federal Republic of Germany, MANNESMANNRÖHREN-WERKE AKTIENGESELLSCHAFT, a German company, of Düsseldorf, Federal Republic of Germany, and SANDVIK AKTIEBOLAG, a Swedish company, of Sandviken, Sweden, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to heat exchangers, for example, steam generators for nuclear power stations, comprising a pressure vessel and a plurality of heat exchange tubes disposed in the pressure vessel and secured in at least one tube plate, through and about which heat exchange tubes the same or different liquid or gaseous media flow. Such devices are of decisive significance for the functioning of power station plant, so that maximum value is to be attached to their reliability. This is all the more the case since manufacture thereof may take years and even simple replacement of faulty devices is, owing to the size thereof and to radioactivity which may possibly have been induced, extremely difficult. Normally, defects in heat exchangers occur only at the heat exchange tubes, when the structure thereof is attacked by external influences, whether these be oscillations or corrosive attack of the heat exchange media.

The experience gathered in recent years has shown that damage caused by corrosion occurs in particular directly adjacent the tube plates and in curved zones of the heat exchange tubes.

It has now been found that the greater part of the damage is due to so-called tension-crack corrosion on the secondary side of the heat exchanger. The prerequisite for the occurrence of tension-crack corrosion is the presence of tensile stresses, but these are unavoidable during manufacture. Since there is frequently no question of stress-relief annealing of the tubes, for reasons connected with strength, it was necessary to seek other solutions for eliminating tensile stresses.

According to one of its aspects the present invention provides a heat exchanger having a plurality of heat exchange tubes, compressive stress having been imparted to a zone of the wall of each tube, which zone is bounded by a surface of said wall, by subjecting said tubes to surface cold-working.

According to another of its aspects the present invention provides a method of manufacturing a heat exchanger, which comprises the step of imparting compressive stress to a zone of the wall of each heat exchange tube, which zone is bounded by a surface of said wall, said step comprising subjecting said tubes to surface cold-working; and the step of assembling the heat exchanger from heat exchange tubes to which compressive stress has been imparted.

When the method is used for the manufacture of a heat exchanger with U-form heat exchange tubes, the step of surface cold-woring is conveniently effected with an apparatus comprising support means for supporting the tubes, and cold-working means, the arrangement of the apparatus being such that, in operation, there is relative movement between each tube and the cold-working means of such a form that the tube can be progressively surface cold-worked along the length thereof.

Expediently each heat exchange tube is provided with internal compressive stress down to a depth of at least 0.1 mm, preferably as much as 0.5 mm, in a separate working step. Owing to the superimposition on the tensile stress originally present of the

subsequently applied compressive stress, there remains a compressive stress excess, so that the occurrence of tension-crack corrosion is prevented. Suitable means for applying such internal compressive stress are *per se* known techniques of cold-working, such as, for example, sand-blasting, hammer forging, and rolling, as already known from German Auslegeschrift No. 1,227,491 which concerns the prevention of tension-crack corrosion in non-magnetic cap rings of austenitic steel for the rotors of electrical machines exposed to the influence of nitrous gases.

Tests have shown that a blast treatment similar to sand-blasting can, with regard to the process data and in particular for straight and also for curved tubes, be relatively readily adjusted and thus adapted and optimised with regard to the tube material employed. Of the above-mentioned methods, in such cases (peripheral) hammer forging also may be employed, and practically identical working devices may be used for the carrying into effect of these working processes.

In order that the invention may be clearly understood and readily carried into effect, reference will now be made, by way of example, to the accompanying drawings, in which:—

Figure 1 shows a sections elevation of a steam generator for a nuclear power station;

Figure 2 shows four plan views of a blasting machine and a U-form heat exchange tube in respective positions on the machine;

Figure 3 shows a sectional elevation of parts of the machine of Figure 2;

Figure 4 shows in elevation a detail of a blasting machine of a form different from that of Figure 3;

Figure 5 shows a plan view of another blasting machine and two U-form heat exchange tubes;

Figure 6 shows an elevation of the machine of Figure 5;

Figure 7 shows a view on line VII—VII of Figure 6; and

Figure 8 shows a view corresponding to that of Figure 7 of a blasting machine of a form different from that of Figure 7.

Referring to Figure 1, the steam generator comprises a vessel 1, a tube plate 14 and heat exchange tubes 15 received therein. For the sake of clarity, only two of the tubes are shown; in reality, there are thousands thereof. The primary medium flows through port stub 11 into a collecting chamber, flows through the tubes 15 and the flows out *via* a further collecting chamber and a port stub 12. The secondary medium to be heated by the primary medium enters *via* a port stub 13, flows about the tubes 15 and flows out as steam *via* an upper port stub 16, water traps being also provided in the vessel 1.

The parts of the heat exchange tubes 15 which are especially sensitive to tension-crack corrosion are located close above the tube plate 14 and are designated *b*; also sensitive are the tube elbows, designated *a*.

The tubes 15 are provided over the entire length thereof with an internal compressive stress which goes deeper than 100 μm, this value depending on the fault depth permissible for the tube material. The thickness of the compressive stressing layer must always be greater than the fault depth since otherwise there is a risk that corrosion phenomena may nevertheless emanate from those faults which penetrate the layer. The level of the compressive stressing must greatly exceed the value of the intrinsic tensile stressing imparted during manufacture of the tubes, since even on the occurrence of supplementary operating stressing it must be made certain that some residual compressive stressing will remain. Taking these aspects into consideration, the thickness range of the compressive stressing layer will normally be approximately 0.12—0.3 mm. In practice, fluctuations of for example 0.14—0.16 mm have been experienced. Thus for safety reasons, it is to be endeavoured to achieve a maximum thickness of the compressive stressing layer of approximately 20—30% of the tube wall thickness, which conventionally is of the order of magnitude of 1—2 mm.

For testing the magnitude and the depth of the compressive stress applied, it is expedient to simultaneously process, during manufacture, tube samples of the same material or to remove a short section from the tubes at the end. However, it is also possible to test the intrinsic compressive stresses by radiographic means or by inductive means, in a non-destructive manner. Special corrosion tests with untreated materials and with materials thus treated — what are concerned are normally asutenitic steels — clearly prove the practically complete insensitivity to tensile crack corrosion of the latter.

Blast treatment of the tubes is very suitable for applying the desired compressive stresses. A suitable blasting medium is glass balls having a diameter of 0.1—0.5 mm, preferably 0.3—0.8 mm, and a degree of hardness higher than that of the material to be blasted. For austenitic stainless steel soda-lime-silicate glass, for example, is suitable. The impingement velocity of these glass balls is a function of the air pressure (approximately 1—10

atmospheres excess pressure) and is advantageously of the order of magnitude of 40—100 m/sec, the spacing of the blasting nozzles relative to the tube surface being 20—200 mm. The velocity of advance of the tube, which is also a function of the number and size of the blasting nozzles, is approximately 5—8 m/min. Apart from glass, other blasting materials having corresponding strength values may also be employed, but it is then necessary to ensure that the material, of which traces may be embedded in the tube surface, will not itself produce corrosion phenomena. Glass has been found to be especially suitable precisely for this reason.

Figure 2 shows a blasting machine for carrying into effect such blasting treatment. This Figure comprises four component views, I, II, III, IV, showing various phases of the process.

Component view I shows a U-form heat exchange tube 15 disposed on a feed roller conveyoer 2. The conveyor 2 comprises horizontal rollers 21 and vertical rollers 22, the spacing of the latter being settable to correspond to the spacing of the limbs of the heat exchange tube 15. The rollers 21 are driven *via* a geared motor 23 to move the tube 15 through a blasting device 4 of the machine.

The blasting device comprises a turntable 42 arranged for pivoting through 180° by a gear motor 44 *via* a pinion 43. Secured on the turntable 42, and radially adjustable to correspond to the limb width of the heat exchange tube, is a blasting nozzle head 41 disposed within a blasting compartment 45 permitting passage of the tube through curtain-like, resilient walls (view II). Disposed at the side of the blasting device further from the conveyor 2 is a return roller conveyor 3 the design of which is similar to that of the feed roller conveyor 2. The conveyor 3 comprises horizontal rollers 31 and vertical rollers 32, the rollers 31 being driven *via* the geared motor 23. The machine is provided with a stop which is a photoelectric cell 33 arranged to switch off the motor 23 and thus terminate the advance of the tube 15 when the full length of one limb of the tube 15 has travelled past the blasting nozzle head 41 (view III). Such stop means can of course also be adjusted, independently of the length of tubes to be blasted, relative to the centre of the tube elbow.

Simultaneously with the switching off of the motor 23, the motor 44 is cut in, thus to turn the turntable 42 and the blasting nozzle head 41 thereon through 180° in the direction of the arrow (view III). Thereby, the elbow of the heat exchange tube 15 is blasted with the same velocity of advance as that at which the conveyor 2 had transported the tube 15 in the direction of the limbs thereof. When the blasting nozzle head 41 has concluded its turning movement, the turning movement is cut out by means of a contact (not shown) and the geared motor 23 is cut in once again, but this time in the opposite direction of rotation. In this manner, the heat exchange tube 15 travels (view IV) back to its starting position, during which travel the other rectilinear limb of the heat exchange tube is blasted. After the tube has reached the starting position, the motor 23 is once again switched off, the processed tube 15 is removed from the supply roller conveyor 2 and a fresh tube is placed thereupon.

Further cutting-in of the motor 23 displaces this fresh tube through the blasting device 4, save that in this case initially the other limb of the tube is blasted first, and then, after the turning movement of the blasting nozzle head 41, the remaining limb is blasted.

Referring to Figure 3, the blasting device 4 is shown in a vertical section. The blasting nozzle head 41 comprises an annular tube on the inner side of which a plurality of nozzles 41*a* are arranged. It is the purpose of the nozzle 41*a* to cause the blasting material to impinge at a desired angle of 55° on the tube 15. The nozzles 41*a* are also so arranged that adjacent blasting streams do not mutually hinder each other but, on the contrary, slightly overlap in respect of their impingement zone, in order that no untreated or inadequately treated areas of the tube remain. The blasting head 41 is, for protecting the environment against the blasting material, surrounded by the box-shaped blasting compartment 45.

The turntable 42 is of funnel shape and is provided with a central, tubulular collar. The turntable is formed with a plurality of apertures 42*a* permitting discharge of blasting material, emerging out of the blasting nozzles, into a container 46 arranged below. The positioning and centring of the turntable 42 is effected with the aid of ball bearings 50 arranged at its edge. Through the tubular collar passes a blasting material supply line 47 which extends in a curve to the blasting head 41. The container 46 is so connected with a filtering device 80 that the collected blasting material automatically travels to that location. In the filtering device, which is constructed in accordance with the principle of the cyclone separator, those blasting material particles which have become excessively small, and therefore useless, are separated-out and supplied, *via* a line 81 to a waste collecting vessel (not shown). Those blasting material particles which are still useful slide to a jet pump 85 connected, *via* a line 48, to a compressor 49,

and associated at the output side with the supply line 47. Therewith, fresh blasting material also can be fed out of a supply container 82, *via* a line 83 and a valve 84, as required to the jet pump 85. The pressure of the pressurised air employed as delivery medium is of the order of magnitude of approximately 5 atmospheres excess pressure. In this manner, it is ensured that the blasting material is delivered along the shortest possible path to the blasting nozzles 41*a* and that minimum frictional losses occur in the transport thereto so that also final velocity losses are minimal.

Of course, other forms also of blasting machines are possible, for example such as the one shown in Figure 4. There the design of the blasting head is the same as in the machine of Figure 3, but the head is secured to a pivoting arm 47*a* which is connected in a manner (not shown) to a supply line for the blasting material. The pivoting arm 47*a* is adjustably connected to a pivot pin 91, so that therewith it is possible to adjust the head relative to the limb spacing of the U-form tube to be treated. Disposed below the pin 91 is a geared motor 44 for pivoting the blasting head 41.

Figures 5 to 7 show another blasting machine in which the heat exchange tubes remain at rest and a blasting device 5 is displaced.

In the case of this machine two heat exchange tubes 15 are fitted over connecting pins 17 and disposed on a plurality of pivoting supports 61. The supports 61 can be hinged down one after the other without the position of the tubes being thereby changed. The two tubes 15 constitute a closed track on which blasting device 5 travels in the manner of a monorailway.

A blasting head 51 (see Figure 7) of the device 5 has practically the same design as the blasting heads 41 of the previously described machines; and is flexibly connected, *via* a supply line (not shown), with a blasting material source (also not shown).

The blasting head 51 is secured to a carriage 53 arranged to travel, with the aid of a profiled roller 57 driven by a geared motor 58, on the heat exchange tubes 15. Support rollers 55 also travel on the tubes 15, and for supplementary lateral guiding a pair of vertically arranged pins 56 are provided. Externally of the track constituted by the heat exchange tubes 15 extends a supporting structure 6, comprising adjustably arranged tubes, on which the carriage 53 bears *via* horizontal rollers 54, thereby acquiring stability. With the aid of the drive motor 58, the carriage 53 travels continuously around the track provided by the heat exchange tubes 15, the blasting head 51 pressing the pivoting supports 61 down so that it is able to travel practically unhindered. After the carriage 53 has passed along one half of the tube track, the heat exchange tube constituting that half can be manually removed and whilst the carriage 53 travels along the other half, the tube which has been removed is replaced by a fresh, untreated tube 15. The heat exchange tubes must in each particular instance be manually replaced in accordance with the travel velocity of the carriage.

An appropriate receiving trough (not shown) is provided for discharged blasting material. The discharged blasting material is then returned *via* a delivery line to a blasting blower, which corresponds to the jet pump 85 of Figure 3.

The imparting of compressive stress to tubes is, as already mentioned, also possible with other methods, such as, for example, hammer forging. A hammer forging machine is shown in Figure 8; it is similar to the machine of Figure 7. In place of the carriage 53 there is provided in this case a carriage 76 to which a peripheral hammer forging device 7 is attached. The device 7 comprises a frame 73 in which there is mounted, by means of rollers 72, a rotary hammering head 71. The hammering head 71 comprises hammer forging units 78 operating in accordance with the resonance principle. Hardened end faces of pins of the units impinge, in the cadence of the system frequency, on the heat exchange tubes 15. The rotation of the hammering head 71 is effected *via* a friction roller 74 from a motor 75 mounted on the carriage 76.

Via rollers 77, the carriage 76 is mounted on a supporting structure 6 and the travel of the carriage is, as in the machine of Figures 5 to 7, effected by a roller 57 (not shown).

The peripheral hammer forging device 7 can, of course, also be introduced instead of the blasting nozzle in the machine of Figures 5 to 7. For the sake of clarity, current supply lines to the individual resonance hammer forging units 78 are not shown in detail; for this purpose sliprings may be employed. Current supply can (as in the case of Figures 5—7) expediently be effected by a trailing cable extending from above.

Instead of an electrical drive, a compressed air drive would be conceivable and this could, of course, also be employed for displacement of the carriage. It would also be possible to design the carriage to depend from the heat exchange tubes so that the outer adjustable supporting structure 6 could be dispensed with.

In the case of each of the examples, the depth of the compressive stressing layer is a

function not only of the tube material but also of the impingement force and density of the blasting material and also of the treatment time, or the corresponding parameters of the hammer forging units 78. Ascertainment of the most advantageous values is a question of tests, the results of which can be ascertained with the aid of the afrementioned methods.

For the blasting processing to tubes it would be possible to employ other delivery and drive processes for the blasting material.

Finally, it should be stated that it is also possible, with the aid of apparatus similar to that used for external compressive stressing which has been modified because of the small space available, to provide the inner walls of heat exchange tubes with compressive stressing in order that there also (if such should be necessary) there is produced a compressive stressing layer which resists tension-crack corrosion.

WHAT WE CLAIM IS:—

1. A heat exchanger having a plurality of heat exchange tubes, compressive stress having been imparted to a zone of the wall of each tube, which zone is bounded by a surface of said wall, by subjecting said tubes to surface cold-working.

2. A heat exchanger as claimed in Claim 1 in which said zone extends from said surface to a depth in an approximate range of 0.1 to 0.5 mm.

3. A heat exchanger as claimed in Claim 1 or 2, said surface having been cold-worked by blasting.

4. A heat exchanger as claimed in Claim 1 or 2, said surface having been cold-worked by hammer forging.

5. A heat exchanger as claimed in any one of Claims 1 to 4, the material of said tube being austenitic.

6. A heat exchanger as claimed in any one of Claims 1 to 5, said surface being the outer cylindrical surface of said wall.

7. A heat exchanger according to Claim 1, substantially as hereinbefore described.

8. A method of manufacturing a heat exchanger which comprises: the step of imparting compressive stress to a zone of the wall of each heat exchange tube, which zone is bounded by a surface of said wall, said step comprising subjecting said tubes to surface cold-working; and the step of assembling the heat exchanger from heat exchange tubes to which compressive stress has been imparted.

9. A method as claimed in Claim 8, wherein said surface is cold-worked by being blased with glass particles having diameters in an approximate range of 0.1 to 1.5 mm.

10. A method as claimed in Claim 9, wherein said diameters are in a range of 0.3 to 0.8 mm.

11. A method as claimed in Claim 9 or 10, wherein said particles are discharged against said surface from a blasting nozzle the discharge end of which is disposed at from about 20 mm to about 200 mm from said surface.

12. A method as claimed in Claim 9, 10 or 11, wherein a gaseous blast medium pressure in an approximate range of 1 to 10 atmospheres is employed.

13. A method according to Claim 8, wherein the step of surface cold-working a heat exchange tube is substantially in accordance with any example hereinbefore described with reference to the accompanying drawings.

14. A method according to Claim 8 for manufacturing a heat exchanger having U-form heat exchanger tubes, in which method the step of surface cold-working is effected with an apparatus comprising support means for supporting the tubes, and cold-working means, the arrangement of the apparatus being such that, in operation, there is relative movement between each tube and the cold-working means of such a form that the tube can be progressively surface cold-worked along the length thereof.

15. A method as claimed in Claim 14, wherein the apparatus further comprises translation means operable to move the tube, in the direction of the limbs thereof, for feeding the limbs through the cold-working means, the cold-working means being arranged for movement along a curved path for the cold-working of the portion of the length of the tube intermediate the limbs.

16. A method as claimed in Claim 15, in which the support means comprises support rollers and guide rollers for guiding said tube.

17. A method as claimed in Claim 15 or 16, in which the cold-working means is a blasting means, the blasting means being mounted on a turntable, and funnel means being provided beneath the blasting means to receive blasting material.

18. A method as claimed in Claim 17, in which a blasting material delivery duct extends to the blasting means, a jet pump is operable to pump blasting material through the duct, and the arrangement is such that material flowing from the funnel means can be fed to the pump.

19. A method as claimed in Claim 15 or 16, in which the cold-working means is mounted on a pivot arm.

20. A method as claimed in Claim 14, in which the cold-working means includes mounting means for co-operation with

track means whereby the cold-working means can be moved along said tube.

21. A method as claimed in Claim 20, in which the track means comprises a U-form track length of the apparatus.

22. A method as claimed in Claim 20 or 21, in which the track means comprises the tube.

23. A method as claimed in Claim 20, 21 or 22, in which the support means comprises a plurality of supporting members each arranged to move out of supporting contact with the tube by the passage of the cold-working means and to move back into supporting contact with the tube when the cold-working means has passed the location of the member.

24. A method as claimed in Claim 21, or Claim 22 or 23 as appended to Claim 21, in which the track means comprises a further U-form track length, the limbs of the two lengths being arranged end-to-end so that a closed loop is provided, thus to permit the cold-working of the tube and a further U-form heat exchange tube disposed relatively to the first mentioned tube so that the two tubes also provide a closed loop.

25. A method as claimed in any one of Claims 14 to 16 or 19 to 24, in which the cold-working means is a hammer forging means.

26. A method as claimed in Claim 25, in which the hammer forging means comprises a hammering device provided with a hammer forging head arranged to rotate about the axis of the tube.

27. A method as claimed in Claim 26, in which the hammer forging head is arranged to operate in accordance with the resonance principle.

28. A method according to Claim 8, wherein the surface cold-working of a U-form heat exchange tube is effected with an apparatus substantially in accordance with any example hereinbefore described with reference to the accompanying drawings.

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4 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

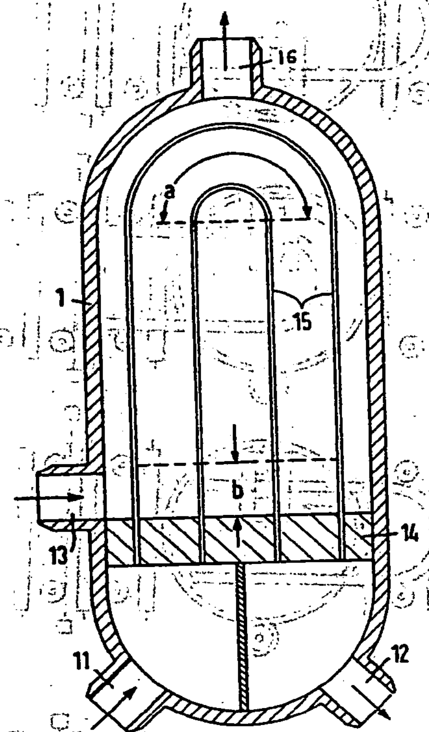

Fig.1

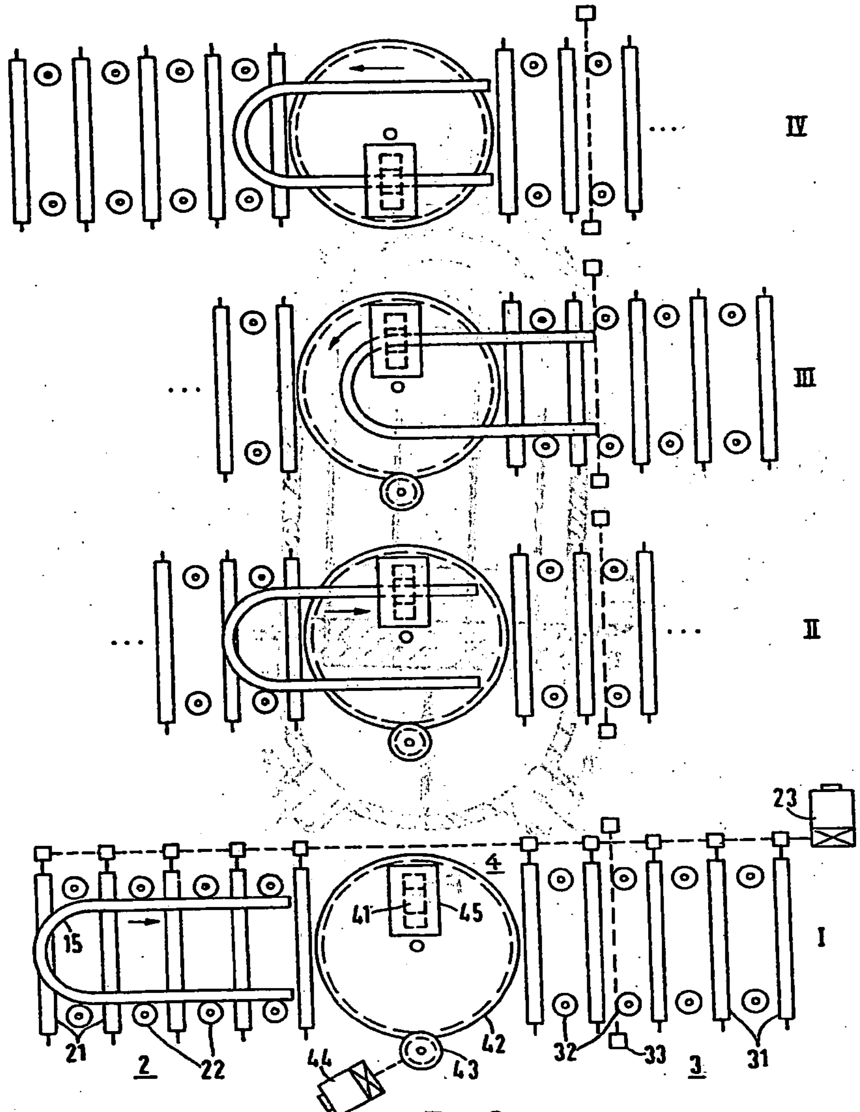

Fig. 2

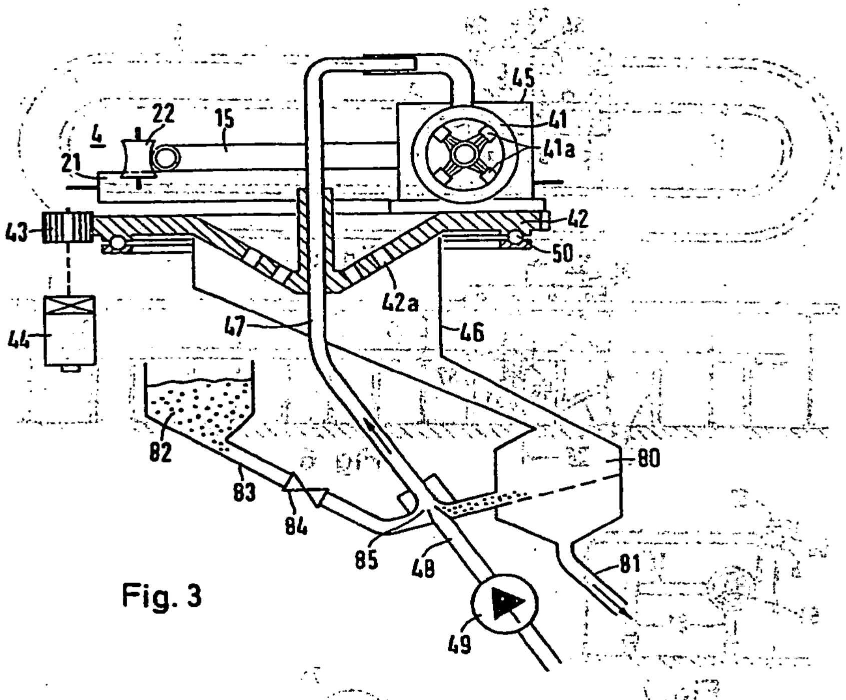
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Fig. 3

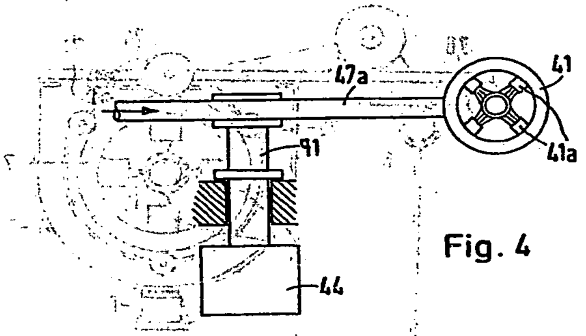
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Fig. 4

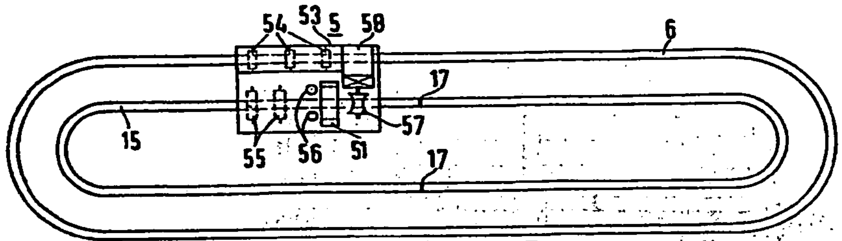

Fig. 5

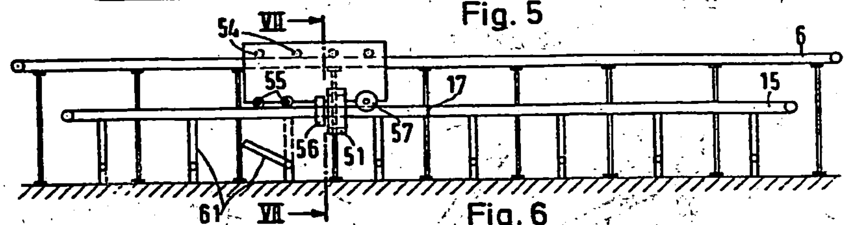

Fig. 6

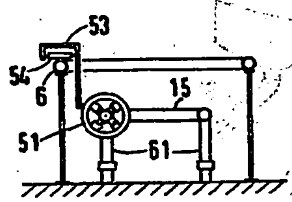

Fig. 7

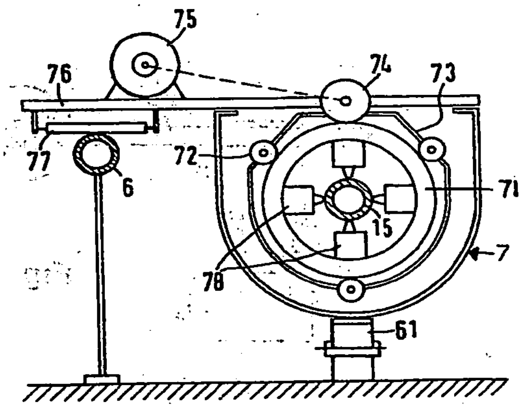

Fig. 8